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Synchronous Generator Loss of Field Protection: A Real-Time Realistic Framework and Assessment of Some Recently Proposed Methods

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Abstract— A real-time realistic framework for synchronous generator loss of field (LOF) protection studies is suggested in this paper by using the real-time-digital-simulator, which allows the user to realistically model the generator field supply circuit. By using such framework, the performance of LOF protection algorithms can be comprehensively evaluated in the face of the various LOF events including the short circuit and two types of the open circuit events, while the open circuit occurrence cannot be studied in the conventional simulation programs. The obtained results demonstrate that the generator dynamics are significantly different in the face of various LOF failures and then all of them must be regarded to develop the new LOF protection algorithms.

By using the suggested framework, the performance of some recently proposed schemes along with the conventional impedance and the admittance relays are comprehensively evaluated. The obtained results from applying the various LOF failures show that, against the conventional relays, the new schemes cannot detect all types of LOF failures and so, they do not have enough reliability.

Index Terms— Synchronous generator protection, Loss of field, Excitation system, Real-time-digital-simulator (RTDS).

I. INTRODUCTION

Loss of field (LOF) phenomenon occurs when the DC source of the generator field is interrupted due to some events such as occurrence of a short circuit or an open circuit in the field circuit, accidental tripping of the field circuit breaker (CB), voltage regulation system failure and loss of the main supply of the excitation system [1]. The LOF protection relay (ANSI code: 40), as one of the most essential protection functions, is considered to trip the generator after an LOF incident [1], when the generator accelerates, starts to operate as an induction generator and draws its excitation from the power system in the form of reactive power.

LOF may cause some undesired effects for both the generator and the power system such as [2]:

1. Heavy overloading of the generator stator winding;
2. Stator end-core overheating;
3. Induced eddy currents in rotor surface resulting in a heavy thermal heating in the rotor body;
4. Torque pulsation and mechanical damages;
5. Voltage drops in the adjacent generators and/or power system with the possibility of a blackout occurrence.

Accordingly, it is vitally important to detect LOF quickly and securely, and isolate the generator from the system to reduce the mentioned consequences.

The primary types of the LOF protection devices including under-current or under-voltage relay [3], which respectively employed field current and field voltage, were unable to cover all types of LOF failures. For instance, the under-voltage scheme could not detect LOF failures caused by opening the field circuit. Moreover, these methods could not correctly discriminate between LOF events and system disturbances, especially stable power swing (SPS) and out of step (OOS) conditions [2].

Nowadays, impedance-based relay (negative offset R-X scheme) [4]-[5] is the most popular scheme for LOF protection in power plants [2]. An LOF is detected when impedance trajectory enters the protective zones with a specified time delay. Although this relay is widely used in the industry [6]-[7], it is always susceptible to mal-operation in the face of system disturbances such as SPS and OOS conditions [8]. As an important example related to LOF relays mal-operations, thirteen mal-operations were reported in North American blackout in August 2003[8].

There are also other types of LOF protection schemes, which are used by the industry, such as positive offset R-X scheme with directional element [9] and admittance-based relay (G-Bscheme) [10].

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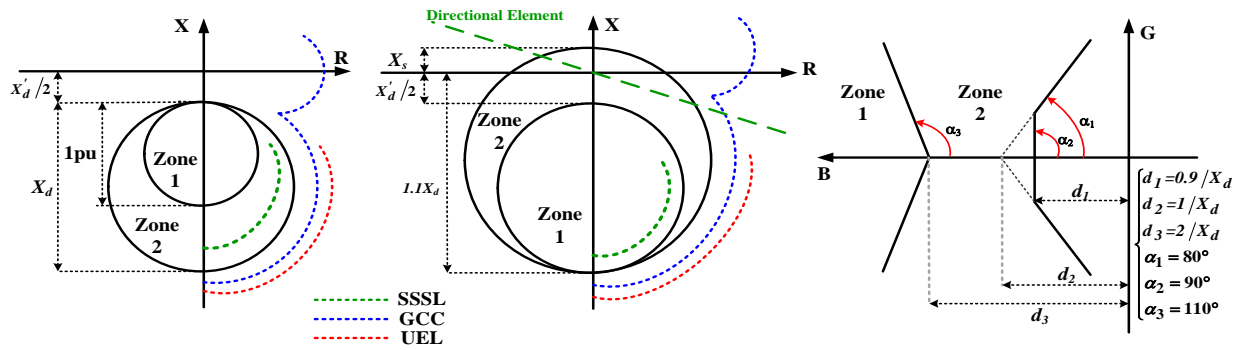


Fig. 1. Charestristic of some industrial LOF relays including negative offset R-X relay (left), positive offset R-X relay with directional element (middle) and G-B scheme (right).

The positive offset R-X scheme detects LOF faster than the negative offset one and the directional element enhances its security against the external short circuit faults [1]. However, its setting is dependent on the system impedance (X_s) and it is still prone to mal-operate during SPS [8]. Figure 1 shows the sample characteristic of the above-mentioned relays, where X_d and X'_d are respectively the synchronous and the transient reactance of the generator.

Time delays for zone1 and zone2 in all the mentioned schemes can be conventionally selected as 0.1 s and 0.5 s, respectively [1]-[10]. However, power swing studies are suggested to better selection of such time delays [1], [8].

There is another problem with R-X schemes that such relays characteristic need to be coordinated with generator capability curve (GCC), under excitation limiter (UEL) and steady state stability limit (SSSL) in R-X plane [11], while such problem can be resolved in G-B scheme, if the UEL characteristic is available [12]. Reference [11] has fully discussed the mentioned coordination issues and has presented an adaptive active power-reactive power (P-Q) scheme to resolve them.

Recently, several new techniques have been proposed in the literature to enhance both the speed and the security of LOF protection, such as:

- Fuzzy Logic (FL), Decision Tree (DT), Adaptive Neuro-Fuzzy Inference System (ANFIS), Artificial Neural Network (ANN) and Space Vector Machine (SVM) based techniques [13]-[17];
Among them, the FLbased method [13] employs the impedance trajectory and generator terminal voltage (V) to improve the conventional R-X scheme performance. DT based technique [14] utilizes V , active power (P) and reactive power (Q) variations to detect LOF. ANFIS based technique [15] employs V , stator current (I) and phase angle between V and I to achieve this goal. ANN based method [16] employs V , I , P , Q and rotor angle (δ) variations to detect LOF and OOS in a single machine system. Finally, the method presented in [17] uses SVM technique to enhance the security of R-X scheme in the face of SPS condition.
Overall, such methods require a considerable amount of data for training and are highly dependent on the system characteristics. In addition, practical implementation of such methods is really a difficult task.
- Flux-based methods [18]-[19];

The method proposed in [18] uses search coils (SCs) which should be placed in the stator slots during generator manufacturing to measure the air gap flux. Moreover, the method presented in [19] estimates the portion of the field flux linked by the stator core by using generator terminal voltage and current signals.

- Setting-free approaches [20]-[22];
The method presented in [20] uses the variation rate of the calculated resistance (R) at the generator terminal to detect LOF. Also, the scheme proposed in [21] uses the second order derivative of generator armature current (I) to detect LOF. The algorithm presented in [22] employs the variations of V , Q and δ to achieve this goal. Although these methods [20]-[22] are setting-free, they require a time delay (e.g. 1.7 s) to detect LOF and discriminate it from SPS.
Although such methods have presented much securer performance than the conventional R-X scheme, (as reported in [20]-[22]), it is shown in this paper that these methods are unable to detect LOF failures caused by the open circuit events in the field circuit.
- Index-based techniques as combination of two or more generator parameters [23]-[25];
The method in [23] uses an index based on variations of V and Q . Although the mentioned index is fast enough, it exhibits mal-operation in the face of SPS [24]. Moreover, time domain simulation studies should be done to achieve the relay setting. Another proposed index in [25] is based on V , Q and δ variations, which requires considering a special operating condition of the network to adjust the relay setting.
- Estimation of the rotor signals [26];
The method presented in [26] estimates the field current (I_f), d-axis damper current (i_d) and consequently field flux linkage for LOF detection. Although the method presented good results, it requires many set points to be identified and it may involve extensive simulation process.
- Excitation and terminal voltages based technique [27];
The method presented in [27] uses both the excitation voltage (V_e) and V for LOF protection in a real power plant and for a particular application. This scheme may not be able to detect less probable field open circuit events, if the field voltage transducer is installed between the field circuit breaker and the field winding [27].

In addition, some research works have investigated the undesirable effect of the flexible alternating current transmission system (FACTS) devices on the LOF protection [28]-[32], while [28] discussed the probable undesirable effects of the midpoint static synchronous compensator (STATCOM) on the conventional R-X relay. It has been shown that the STATCOM affects impedance trajectory and increases LOF detection time for such relay. The SVM and ANN techniques have been suggested to compensate the mentioned effect. Also, references [29]-[31] have employed phasor measurement units (PMUs) along with the communication links to correct the impedance seen by the conventional LOF relays in the presence of FACTS devices. Also, reference [32] discussed STATCOM effects on the flux-based method that had been presented in [18].

In all, every technique needs to be verified through the experimental setups or software simulators [33]-[35]. However, the generator model available in such simulation programs has some limitations to model the various LOF events in the generator field circuit. For example, LOF event can only be simulated by zeroing the field voltage (short-circuit), while according to IEEE Standard C37.102-2006 [1] it can occur in practice due to open circuiting of the field circuit and so on. The real-time-digital-simulator (RTDS) [36] provides a different alternative principle for generator modeling which allows the user to consider a proper realistic field circuit for the generator. By using the RTDS, all types of LOF failures and consequently LOF protection schemes can be modeled and evaluated. Therefore, the pros and cons of such schemes in the face of various types of LOF failures become clearer.

The rest of this paper is organized as follows:

Section II briefly investigates the most important methods of the generator modeling in power system simulation programs. Section III discusses the RTDS capabilities for LOF protection studies and suggests a realistic framework for this purpose. Moreover, simulation studies are done in this section by using a sample single machine connected to an infinite bus (SMIB) system to clarify the superiority of such framework in compare to the conventional simulation programs. In continuous, the performance of some new research works [20]-[23] published in this field are examined and discussed in Section IV by using the suggested framework in Section III. Finally, the paper is concluded in Section V.

II. SYNCHRONOUS GENERATOR MODELING METHODS IN SIMULATION PROGRAMS

Synchronous generator modeling has been a popular research subject for quite a long time. Considering the objective of such studies, modeling approaches can be roughly divided into three categories [37], including:

1. Finite Element Method (FEM);
2. Equivalent Magnetic Approach (EMA);
3. Coupled Electric Circuit (CEC) approach.

This section briefly discusses the last approach which has been very often utilized to investigate the dynamic behavior of

the generator in power system studies.

Phase-domain (PD) model is the original form of the CEC model in which the generator is modeled as a set of mutually coupled time-varying inductances. This approach performs the simultaneous solution for the machine and the electrical variables of the network [37]-[38]. However, since the complicated time-variant self and mutual inductances of the PD model results in a heavy computational burden for modeling the stator and rotor circuits, this model has not been used in the conventional simulation programs [37].

To simplify the CEC further, the physical variables of the machine are often transformed into two-axis ($d-q$) coordinate frames by using the well-known Park transform [3] ($d-q$ modeling), which is widely used in power system simulation programs as a more convenient solution [37]. The $d-q$ model is well-suited for use in power system stability studies in which the dynamic response of the generator to the external disturbances is of major interest [39]. Although this approach greatly reduces the structural complexity of the generator model, certain details on the generator cannot be represented as a result of this simplification [38]-[39]. For instance, LOF failure due to field open circuit and stator/rotor winding faults cannot easily be represented in this model [39].

In the recent years, a real-time PD model for synchronous generator has become available on the RTDS software (RSCAD) library [36], which allows representation of the faults in the excitation systems feeding the field winding of the generator in addition to the faults in the stator windings [36]. Figure 2 illustrates the PD type of generator model in the RTDS along with the general schematic diagram of $d-q$ model, which is available in popular simulation programs [33]-[35]. As can be seen, both ends of the field winding are accessible in this model, while they are connectable to a desired electrical circuit as an excitation system. In other words, this model allows simulating the realistic short circuit or open circuit occurrence on the excitation system, while LOF just can be simulated in $d-q$ model by zeroing the V_F , i.e. the short circuit of the field.

Universal generator model available in ATPDraw software [40] is another tool to do the comprehensive LOF studies. In all, each software/simulator with the ability to apply the mentioned various LOF types can be used to achieve this aim. However, the RTDS allows hardware-in-the-loop (HIL) testing. Such capability admits to imply the various protective algorithms on the industrial relays/platforms for different scenarios in real-time condition, as well [26], [41].

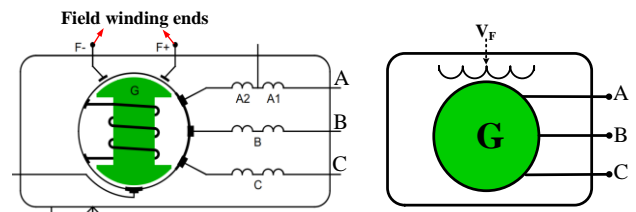


Fig. 2. Schematic plan of the generator models including PD model in RTDS [36] (left) and $d-q$ model in the conventional programs [33]-[35] (right).

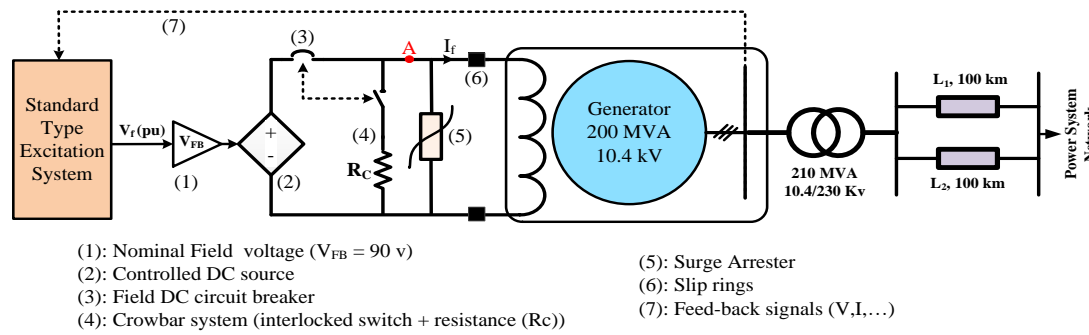


Fig. 3. Sample SMIB system modeled in RSCAD with a detailed excitation system.

III. LOF STUDIES ON A SMIB SYSTEM BY USING THE PD GENERATOR MODEL IN THE RTDS

A. Sample system

By using PD generator model in the RTDS, a sample SMIB system is developed as a realistic framework to study the LOF phenomenon. Figure 3 shows the single line diagram of the SMIB system with detailed excitation system for the generator. In this framework, all available standard types of the excitation systems [42] can be used. The output per-unit voltage of such a system multiplied by the nominal field voltage (V_{fb}) of the generator is applied to the field circuit. V_{fb} is needed to produce a nominal terminal voltage ($V=1$ pu) in no-load condition, while it is available from the generator open circuit test data [3]. It should be noted that, any other arbitrary excitation system such as three phase static rectifier based one [43]-[44] can be constructed and used in this framework. In the simulated SMIB system, IEEE-T1 and IEEE-G1 models are used for the excitation and governor systems, respectively, as presented in [42] and [45].

Three most important types of LOF considered in this paper are as the following:

- Type-1: Short circuit occurrence in the excitation system, e.g. at point A of Fig. 3.
- Type-2: DC circuit breaker opening and crowbar activation with interlock mechanism.
- Type-3: Open circuit occurring in the excitation system, e.g. at point A of Fig. 3, and surge arrester self-activation to suppress the field winding overvoltage.

Notice that only the first one can be simulated in the conventional simulation programs [33]-[35]. It should be noted that the value of crowbar resistance (R_c) is normally selected equal to 3-5 times bigger than the field winding resistance (R_f) as regarded in [19],[46]-[47]. More detailed data for the studied system is provided in the appendix.

B. Generator dynamics during various LOF failures

Case1: Heavy load condition

In this case, the generator delivers $0.9+j0.25$ pu in the steady state condition. All kinds of the LOF Types are examined. Figure 4 depicts the variations of the generator output parameters including δ , V , I and Q for this case. $\delta_c=150$ is assumed as the critical value for δ , while the generator loss of synchronism (LOS) occurs due to the LOF failure. The generator output parameters such as V and Q will swing by the

slip frequency [2] after LOS occurrence, while the second and third types create much faster LOS occurrence than the first one (LOF due to short circuit).

Case2: Light load condition

In this case, the generator delivers $0.3+j0.1$ pu in the steady state condition. As shown in Fig. 5, the variations of δ , V , I and Q for this case are appeared with more time delay than the heavy loading condition. However, generator dynamics after LOF failures caused by open circuit failures are still much faster than that caused by short circuit fault. It should be noted that in addition to loading level, other parameters such as short circuit capacity (SCC) of the external grid and power factor may affect the generator dynamics [2]. However, Fig. 4 and Fig. 5 are represented to show that how much generator dynamics can be different in the face of various LOF failures in asimilar condition.

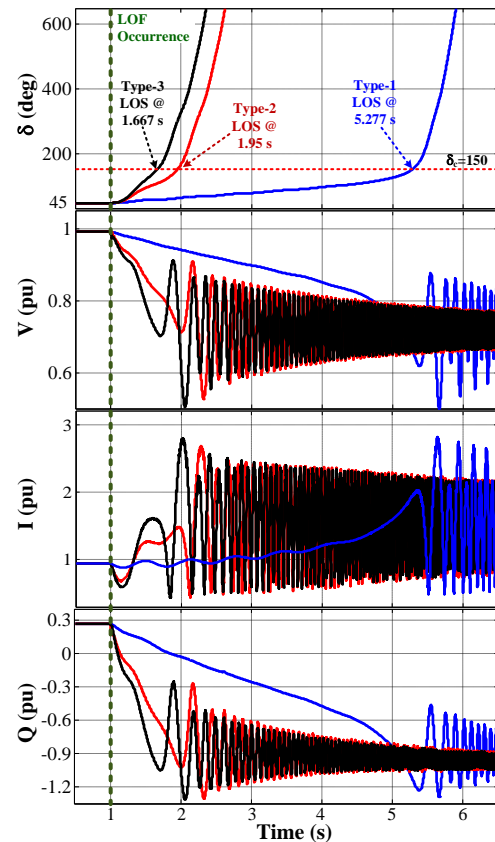


Fig. 4. δ , V , I and Q variations during all types of LOF failures in Case1.

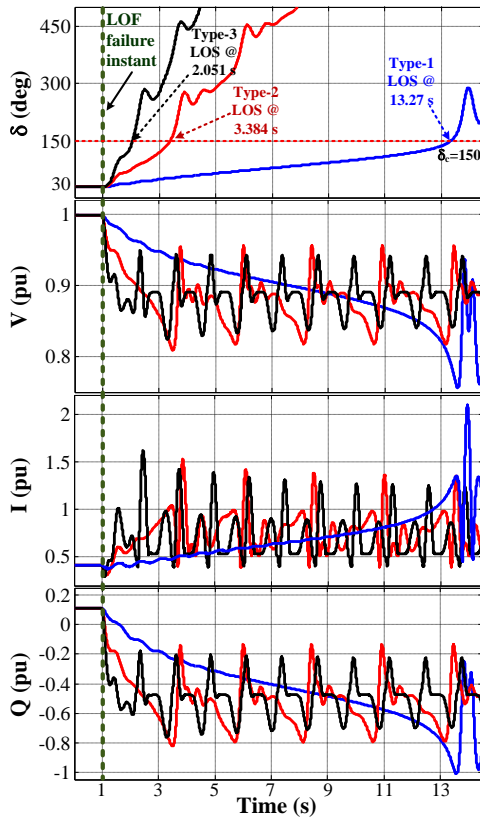


Fig. 5. δ , V , I and Q variations during all types of LOF failures in Case2.

C. A brief justification for generator dynamic during different LOF failures

As can be resulted by looking at Fig. 4 and Fig. 5, in a specific loading, the generator dynamic depends on the type of LOF failure, so that LOF failures that are caused by open circuiting of the field with crowbar/surge-arrester activation (which cannot be simulated in the conventional programs [33]-[35]) make much faster changes in the generator variables than those caused by the other type. These types of the LOF failures may seriously affect the performance of the LOF protection methods reported in the literature.

After an LOF failure occurrence, field DC current decays at a rate determined by the field circuit time constant [2]. So, the magnetic coupling between the rotor and the stator starts to weaken and finally cause generator LOS [2]. After that, generator parameters oscillate with slip frequency (induction generator mode).

Figure 6 shows the generator field winding conditions (from viewpoint of A in Fig. 3) during the mentioned LOF failures where L_f and R_{SA} are respectively the field winding inductance and the surge arrester non-linear resistance. Surge arrester parameters and its V - I characteristic (as described in [26] and [36]) are presented in appendix. Due to LOF occurrence, field current (I_f) will be expressed as (1) including two components: decaying exponential component (I_{DEC}) which decays over the time and alternating component (I_{AC}) due to rotor slipping of $s(t)$ [46]:

$$I_f(t) = \underbrace{I_{f0}e^{-\frac{t}{\tau}}}_{I_{DEC}} + \underbrace{I_m(t) \cdot \sin(s(t) \times \omega_s t)}_{I_{AC}} \quad (1)$$

where I_{f0} , τ , I_m , ω_s and $s(t) = \frac{\omega_s - \omega(t)}{\omega_s}$ are the pre-fault value of I_f , the field circuit time constant, the amplitude of the induced AC current in the rotor winding, synchronous rotor speed and the rotor slip, respectively.

It is clear that during LOF phenomenon, rotor slip will be increased and consequently the induced AC current component (I_{AC}) will exhibit incremental behavior in both the amplitude and the frequency [2], [46]. Also, due to crowbar or surge arrester resistance (as shown in Fig. 6), field circuit time constant decreases, so that τ_1 is bigger than both of τ_2 and τ_3 (although the related behaviors cannot be modeled as pure R-L circuits and will be affected by the induced AC voltages because of rotor slipping). So, it can be anticipated that the field current during the second and third types of LOF failures decays faster (and accordingly, LOS occurs sooner) than the first one.

Figure 7 illustrates the variation of I_f for all three types of LOF failures in Case1, which is in accordance with the above-mentioned descriptions for I_f behavior.

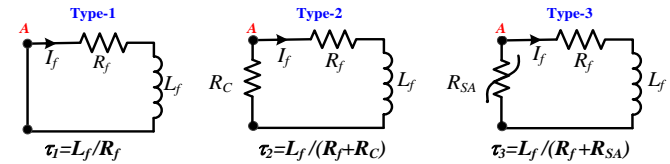


Fig. 6. Generator field circuit conditions during various LOF failures.

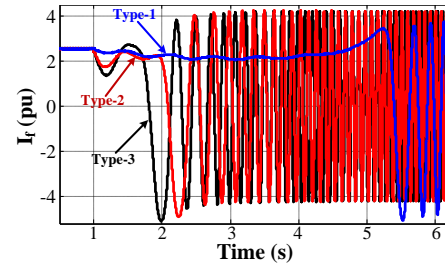


Fig. 7. Generator field current during various LOF failures in Case1.

IV. ASSESSMENT OF SOME RECENTLY PROPOSED TECHNIQUES FOR LOF DETECTION

As illustrated in the previous section, synchronous generators exhibit different dynamics in the face of various LOF failures. Moreover, as before mentioned, most of the recent research works reported in the literature have employed conventional simulation programs [33]-[35] in which the LOF phenomenon cannot be studied comprehensively as can be done in the presented framework by using the RTDS according to the related capability to model the various types of LOF failures. To show the effectiveness of this framework, the performances of the proposed techniques in the recent research papers, including:

- An approach based on derivative of R [20];
- An approach based on the second derivative of I [21];
- An approach based on V , Q , and δ variations [22];
- An index based on V and Q derivatives [23];

Are investigated, discussed and compared with the

conventional R-X scheme [5]-[7] and the G-B scheme [10].

In all abovementioned references, only the first type of the LOF failures (with a long time constant) is employed to evaluate the associated algorithms by using the d - q model for the generator. Thus, by choosing an appropriate time delay (which is selected based on the minimum swing frequency of power system namely 0.3 Hz [20]-[22]), this type of LOF failure can be easily detected and discriminated from the other transients such as SPS.

In the following, these algorithms are briefly described.

A. LOF detection based on derivative of R [20]

A setting-free algorithm, which is presented in [20], employs the derivative of R as below:

$$\text{If } \frac{dR}{dt} < 0 \xrightarrow{\text{for } 1.7s} \text{LOF is occurred} \quad (2)$$

The first row of Fig. 8 illustrates the performance of this method in the face of the various LOF failures in Case1. As can be seen, this approach can detect the Type-1 LOF. However, it is unable to detect other types of LOF failures because of the fast and bipolar variations of $\frac{dR}{dt}$, which is rooted in LOS phenomenon.

B. LOF detection based on the second derivative of I [21]

The proposed method in [21] uses the second order derivative of the armature current (SODAC) to detect LOF as a setting-free based on the following logic:

$$\text{If } \text{SODAC} = \frac{d^2I}{dt^2} > 0 \xrightarrow{\text{for } 1.7s} \text{LOF is occurred} \quad (3)$$

The second row of Fig. 8 exhibits the performance of this technique. As can be seen, this method cannot detect the second and the third type of LOF failures, similar to the previous technique.

C. LOF detection based on V , Q and δ variations [22]

The setting-free method presented in [22] uses V , Q and δ variations (VQ δ method) to detect LOF by using the following logic:

$$\text{If } \left\{ \begin{array}{l} \Delta V^k < 0 \\ \text{and} \\ \Delta Q^k < 0 \\ \text{and} \\ \Delta \delta^k > 0 \end{array} \right\} \xrightarrow{\text{for } 1.7s} \text{LOF is occurred} \quad (4)$$

where $\Delta V^k = V^k - V^{k-1}$ and $\Delta Q^k = Q^k - Q^{k-1}$ and $\Delta \delta^k = \delta^k - \delta^{k-1}$ are respectively the variation of V , Q and δ in two consecutive samples.

The third row of Fig. 8 shows the performance of this approach in the face of LOF failures. As can be seen again, this method cannot detect the second and third types of LOF failures, too.

D. LOF detection based on V and Q derivatives [23]

The proposed method in [23] detects the LOF failures by using an introduced LOF protection index (LOFI) on the basis of V and Q derivatives as:

$$\text{LOFI} = 10^5 \times \Delta V^k \times \Delta Q^k \quad (5)$$

where ΔV^k and ΔQ^k are introduced similar to the previous

method.

The LOF detection logic for this index is presented as below:

$$\text{If } \text{LOFI} > T_h \xrightarrow{\text{for } 1s} \text{LOF is occurred} \quad (6)$$

where T_h is a predefined threshold value that must be chosen based on the simulation studies.

The forth row of Fig. 8 shows the performance of this technique in the face of various types of LOF failures. As can be seen, although LOFI method detects the first and second types of LOF failures, it is unable to detect the third one.

E. LOF detection by the conventional R-X [5]-[7] and G-B [10] schemes

The fifth and sixth rows of Fig. 8 show the performance of the conventional R-X [5]-[7] and G-B [10] schemes in the face of different types of LOF failures. As can be seen, against the abovementioned methods, these relays detect all types of the simulated LOF failures and operate reliably.

The performance of the all abovementioned techniques in various loading levels are summarized in Table I, where the cases 1-4 and 5-7 are respectively related to the various loading levels in lagging and leading power factors. It can be concluded from this table that:

- The recent developed methods [20]-[23] cannot reliably detect LOF failures caused by opening of the field circuit, i.e. Type-2 and Type-3.
- LOFI and VQ δ methods generally can detect the Type-1 LOF failures faster than the conventional scheme.
- The conventional scheme covers all types of LOF failures.

Indeed, the conventional R-X [5]-[7] and G-B [10] relays are enough to reliably diagnose all types of LOF failures. However, they are always susceptible to mal-operate during system disturbances such as SPS and OOS conditions. As reported in the literature [13]-[32], increasing the security and the speed of such relays are two main objectives that have led the researchers to develop new LOF protection schemes. Although, such goals are achieved by some of the recently proposed techniques, such methods have not paid enough attention to the reliability as a vital protection factor. Such reliability must be evaluated based on IEEE Standard C37.102-2006 [1] through a realistic framework to model different types of LOF failures.

F. Performance assessment of different methods in the face of SPS and OOS conditions

From the security point of view and as reported in [20]-[23], $\frac{dR}{dt}$, SODAC and VQ δ methods are more secure in the face of SPS than the conventional R-X scheme [5]-[7].

The obtained simulation results in this section will show that the R-X [5]-[7] and G-B [10] schemes with the conventional settings are susceptible to exhibit mal-operation in the face of non-LOF system disturbances (e.g. SPS and OOS), as the main goal of researchers to develop new secure LOF protection schemes.

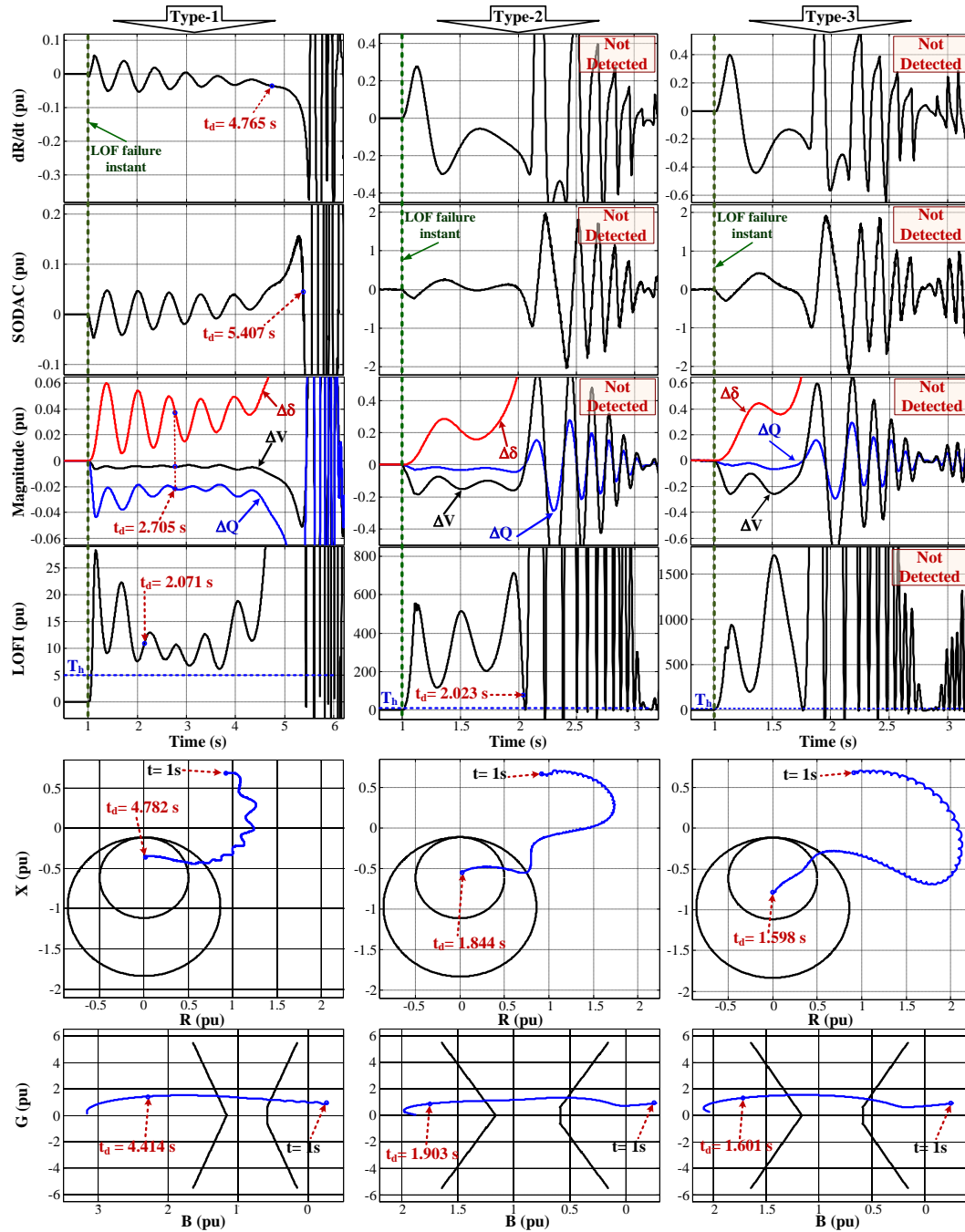


Fig. 8. Comparing of different techniques performance in the face of LOF failures in Case1 (heavy load) including dR/dt [20] (the first row), SODAC [21] (the second row), $VQ\delta$ [22] (the third row), LOFI [23] (the forth row), the conventional R-X technique [5]-[7] (the fifth row) and G-B scheme [10] (the sixth row).

1) SPS occurrence

Figure 9 (left column) shows the performance of the mentioned methods in the face of a sample SPS condition. To create such a condition, when the generator initially delivers $0.4-j0.3$ pu, a three phase short circuit fault is applied to the middle of L1 at $t=1$ s. The fault is cleared after 350 ms by circuit breakers opening in both ends of L1. So, the system experiences an SPS condition. As shown in Fig. 9 (left column), all recently proposed methods are secure in such condition and do not exhibit mal-operation. This is because of that LOF detection criterion is not achieved during SPS

condition. Indeed, time settings to detect LOF in such schemes are large enough to avoid mal-operation. For instance in $\frac{dR}{dt}$ based scheme, it is crucial that $\frac{dR}{dt}$ takes the negative values for 1.7 s to detect an LOF, while the mal-operation will be avoided due to the fast bipolar variations of $\frac{dR}{dt}$, as shown in Fig. 9 (the first row). Conversely, the conventional R-X and G-B schemes with the related time settings can cause an unwanted generator tripping, while they are unable to discriminate such a condition from LOF occurrence.

TABLE I. COMPARING OF THE PERFORMANCE OF RECENTLY PROPOSED LOF PROTECTION METHODS WITH THE CONVENTIONAL R-X AND G-B SCHEMES

#	Loading P+jQ (pu)	LOF Type	Performance Assessment (Operation Time/ Not Detected (ND))					
			dR/dt [20]	SODAC [21]	VQδ [22]	LOFI [23]	R-X [5]	G-B [10]
1	0.9+j0.2 (Lagging PF)	1	3.765	4.407	1.705	1.071	3.782	3.414
		2	ND	ND	ND	1.023	0.844	0.903
		3	ND	ND	ND	ND	0.598	0.601
2	0.7+j0.5 (Lagging PF)	1	5.619	6.299	1.707	1.083	5.143	4.83
		2	ND	ND	ND	1.038	1.149	1.213
		3	ND	ND	ND	ND	0.721	0.769
3	0.5+j0.3 (Lagging PF)	1	5.56	7.375	1.711	1.092	6.967	6.818
		2	1.954	ND	1.706	1.011	1.666	1.636
		3	ND	ND	ND	ND	1.063	1.022
4	0.3+j0.1 (Lagging PF)	1	4.764	5.383	1.713	1.134	9.012	9.137
		2	2.881	ND	ND	ND	1.913	1.954
		3	ND	ND	ND	ND	1.061	1.029
5	0.8-j0.2 (Leading PF)	1	4.035	5.252	1.71	1.116	3.151	2.809
		2	ND	ND	ND	ND	0.825	0.925
		3	ND	ND	ND	ND	0.506	0.541
6	0.5-j0.5 (Leading PF)	1	1.709	5.781	1.726	1.173	2.039	2.504
		2	ND	ND	ND	ND	1.086	0.876
		3	ND	ND	ND	ND	0.479	0.592
7	0.3-j0.1 (Leading PF)	1	1.726	5.941	1.738	1.203	9.143	9.579
		2	ND	ND	ND	ND	1.319	1.462
		3	ND	ND	ND	ND	0.479	0.592

2) OOS occurrence

To create an OOS condition, a three phase short circuit fault with clearing time of 360 ms is applied on the middle of L1, while the generator initially delivers 0.6-j0.4 pu. Figure 9 (right column) illustrates the performance of different schemes in the face of such a condition. As can be seen, all the recently developed methods [20]-[23] behave securely in the face of this condition, due to the fast and bipolar variations of the used indices. Alternatively, the R-X and G-B schemes exhibit mal-operation during such condition.

V. CONCLUSION

It is shown in this paper that evaluating the proposed LOF protection techniques must be done in a comprehensive environment, such as the RTDS. Therefore, a realistic framework is suggested for this purpose by using the phase domain generator model in the RTDS, which allows the user to model the generator field circuit with more details and apply the various types of the probable LOF events in the generator field circuit as mentioned in IEEE Standard C37.102-2006.

Simulation studies carried out on a SMIB system approved that the various generator dynamics during different types of LOF events must be considered to develop the new LOF protection algorithms, while it is shown in this paper that some of the recently proposed schemes (against the conventional R-X and G-B ones) are unreliable to detect LOF failures caused by the field open circuit events. Therefore, the effectiveness of the suggested framework developed in the RTDS becomes clear in comparison with the conventional power system simulation programs.

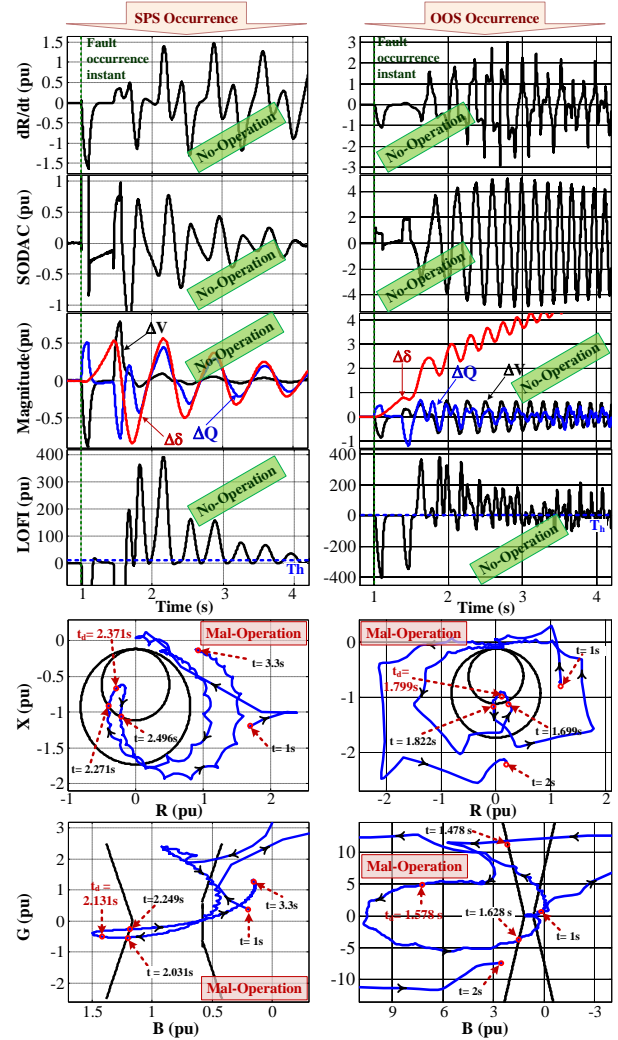


Fig. 9. Comparing of different techniques performance in the face of sample SPS (left) and OOS (right) condition including dR/dt [20] (the first row), SODAC [21] (the second row), VQδ [22] (the third row), LOFI [23] (the fourth row), conventional R-X scheme [5]-[7] (the fifth row) and the G-B scheme [10] (the sixth row).

APPENDIX A

TABLE A1. SMIB SYSTEM PARAMETERS

Synchronous Generator	Transformer	Lines (L1&L2)
$S=200$ MVA, $f=50$ Hz, $V=10.4$ kV, $H=3.165$ s, $X_l=0.1$ pu, $R_s=0.0012$ pu $X_d=1.72$ pu, $X'_d=0.23$ pu, $X''_d=0.2$ pu, $X_q=1.66$ pu, $X'_q=0.2$ pu, $X''_q=0.2$ pu, $T'_{do}=8.125$ s, $T''_{do}=T''_{qo}=0.0272$ s	$S=210$ MVA, $10.4/230$ kV $Uk\%=8\%$	$L=100$ km $Z^+=0.0185+j0.376$ Ω/km $Z^-=0.361+j1.227$ Ω/km

TABLE A2. EXCITATION SYSTEM PARAMETERS

IEEE Type-1 standard system [41]	Crowbar	Surge Arrester [36]
$Tr=0$ s, $Ka=200$, $Ta=0.02$, $Ke=0.1$, $Te=0.4$, $Kf=0.0345$, $Tf=1.5$, $E1=6.08$, $Se1=0.062$, $E2=6.83$, $Se2=0.132$, $Vmax=10.33$, $Vmin=-3.6$	Crowbar resistance: $R_c=1\Omega$ (Field resistance: $R_f=0.2\Omega$)	Discharge Voltage: $V_d=1.2$ Kv Discharge Current: $I_d=10$ KA $N=16$ $I = I_d \left[\frac{V}{V_d} \right]^N$

TABLE A3. GOVERNOR PARAMETERS

IEEE Type-G1 Governor
$K=10$, $T1=0.05s$, $T2=0.05s$, $T3=0.05s$, $T4=0.22s$, $T5=5s$, $T6=0.1s$, $T7=0.1s$, $U_0=0.1$, $U_c=-10$, $K1=0.27$, $K2=0$, $K3=0$, $K4=0$, $K5=0.25$, $K6=0$, $K7=0.48$, $K8=0$, $P_{max}=1$ pu, $P_{min}=0.1$ pu,

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